Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering
OMAE2008
June 15-20, 2008, Estoril, Portugal

OMAE2008-57434

Using CFD to study the effects of staggered buoyancy on drilling riser VIV

Samuel Holmes
Red Wing Engineering, Inc.

Owen H. Oakley, Jr.
Chevron Energy Technology Company

Kamaldev Raghavan
Chevron Energy Technology Company

Yiannis Constantinides
Chevron Energy Technology Company

ABSTRACT

This paper examines the potential benefit of the spaced arrangement of buoyancy modules to reduce the vortex induced vibration of deepwater drilling risers. Buoyancy modules are most often continuously applied to a riser to manage the top tension in the riser but they can also be spaced apart so that segments of bare riser are exposed. Field experience suggests this "staggering" of the buoyancy modules tends to suppress vortex induced vibration (VIV). However, the effects of staggered buoyancy are not well understood. In this paper we use CFD simulations to find the flow characteristics of various combinations of buoyancy modules and bare sections which include choke and kill lines. The effect of varying the percentage of buoyancy coverage is estimated based on the forced and free vibration characteristics of individual sections and combinations of the sections. Some direct reduction in VIV was observed but the benefits seem small.

INTRODUCTION

Drilling risers tend to be very heavy and are often installed with high pressure foam buoyancy in order to reduce the load on the riser tensioners. Figure 1 shows a drilling riser with three spaced buoyancy modules. The bare sections, called "slick joints", have the riser, choke and kill lines and control umbilicals exposed as illustrated in Figure 1. Although reducing the number of buoyancy modules may increase the tensioner loads, a few slick joints can generally be tolerated in the riser string in the high current region if their presence helps to reduce vortex induced vibrations (VIV). With this in mind the "staggered buoyancy" configurations studied here conform to normal deepwater drilling practice. Note that although changes in tension may change the modes of vibration of the riser structure this effect is thought to be small. However, changes in section

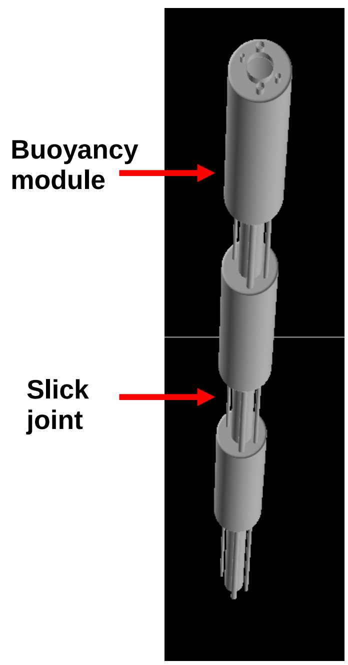

Figure 1. Drilling riser with buoyancy modules

diameter will change the vortex shedding frequency since it varies inversely with diameter.

Although field experience suggests that distributing buoyancy modules along a riser does affect VIV and might be used to reduce it [1], the mechanisms of these affects are not well understood. As a long flexible system, a riser has a wide range of possible modes of vibration and natural frequencies that might be excited by vortex shedding. Changing the buoyancy arrangement changes the natural models of the structure but

Copyright © 2008 by ASME

also changes its vortex shedding characteristics. Our own examination of the effect of changing tension on vibration frequency and mode shape showed this affect to be small. Furthermore, recent laboratory experiments by Vandiver and Peoples and Vandiver et al. [2,3] do not show a great benefit from staggered buoyancy arrangements. In this study, a series of experiments were conducted with a simplified model of a drilling riser consisting of a single small diameter cylindrical pipe with various staggered arrangements of larger diameter buoyancy sections. Note that this model does not include the potential effects of the added choke and kill lines and umbilicals found on drilling risers providing one of the motivations for the current work. As a result of their experiments, Vandiver and Peoples concluded that the primary benefit of adding buoyancy might be to increase the effective diameter of the riser reducing the vortex shedding frequency and modes of vibration and thus reducing fatigue damage rate. However, as they point out, the increase in diameter also tends to increase drag as well as the displacements resulting from VIV offsetting some of the benefits from the reduced frequency of vibration. Although these observations point to some benefit from staggered buoyancy arrangement, they do not seem to coincide with field experience i.e. that staggered buoyancy helps reduce the occurrence of VIV.

Laboratory scale field experiments [4] have shown that riser VIV is complex phenomenon and may not often consist of a simple standing wave response at a single harmonic frequency. The experiments in [4] suggest that "traveling" waves play a significant role in the response. Thus the motion at any point or along any short section or "element" is not periodic and the local element in the riser is forced to continually undergo a changing response. Traveling waves are expected if the current speed and direction vary along the riser. In order to characterize risers under these conditions it is common to think of some elements of the riser as excited by local vortex shedding where the fluid forces are mostly in phase (in a vector sense) with the local velocity so that the work done on the riser is positive. These "power-in" elements put energy into the riser system. On the other hand, other elements are forced to undergo motions in such a way that the forces are out of phase with the velocity and are called power-out" elements. These elements are dissipating energy and damping the riser motions. Under these conditions, one might expect a riser to show reduced vibration if the individual sections show weak or uncorrelated vortex shedding, if the forces associated with VIV are reduced or if some sections introduce significant damping. It is with this in mind that we seek to characterize the vortex shedding characteristics of the buoyancy and slick sections of the drilling riser. It certainly seems likely that if vortex shedding from the buoyancy sections dominates the response, and the slick sections provide damping, reducing the number of buoyancy sections in high current regions will reduce VIV.

Perhaps the simplest experiment to characterize a riser section is to subject it to forced vibration in a tow tank while varying tow speed and vibration amplitude. The lift and displacement histories can be combined to calculate lift in phase with velocity (C_{lv}):

$$C_{lv} = \frac{2}{T_d a_1 F_1}\int_{t_1}^{t_2} f_y(t)\frac{dy(t)}{dt}dt \qquad (1)$$

where t is time, T_d is the sample time interval length ($(t_2 - t_1)$, $y(t)$ is the crossflow displacement, $f_y(t)$ is the instantaneous lift force and where

$$a_1^2 = \frac{2}{T_d}\int_{t_1}^{t_2} (\frac{dy(t)}{dt})^2 dt$$

and

$$F_1 = \frac{1}{2}A\rho U^2$$

Where A is the frontal area and ρ is the fluid density. Positive values for C_{lv} in equation (1) indicate a power in response under the given tow speed and motion conditions while negative values indicate a damping response.

In the remainder of this work, we use computational fluid dynamics (CFD) to establish the hydrodynamic characteristics of typical drilling riser elements, i.e. buoyancy sections and slick joint sections undergoing forced vibration in cross flow only. The objective is to find characteristics that might be used to reduce VIV. We look for buoyancy configurations that will improve performance by reducing excitation and increasing damping. We then perform some limited simulations of drilling riser sections in free vibration with both cross flow and in-line degrees of freedom to determine whether combined sections have an obvious direct benefit.

APPROACH

We first look at the riser VIV problem using short sections of the riser components in forced vibration. We limit riser motions to simple sinusoidal motions in the cross-flow direction only, recognizing that actual motions will usually include in-line components as well. A typical drilling riser has a central pipe with four external lines of varying diameters. These are the choke and kill lines. The arrangement used here is shown in Figure 2 which shows part of a buoyancy section with protruding drilling riser with auxiliary lines. The buoyancy module shown in Figure 2 has an overall diameter of 1.27m while the drilling riser has a diameter of 0.53m. The two larger peripheral lines (the choke and kill lines) have a diameter of 0.165m and the remaining lines have diameters of 0.114m and 0.089m. Note that the figure also shows the surface descretization used in the CFD solution.

As shown, the drilling riser with its auxiliary lines forms a system without azimuthal symmetry. We picked two headings representing quite different configurations for the simulations use here with the objective of finding extremes in response,

Copyright © 2008 by ASME

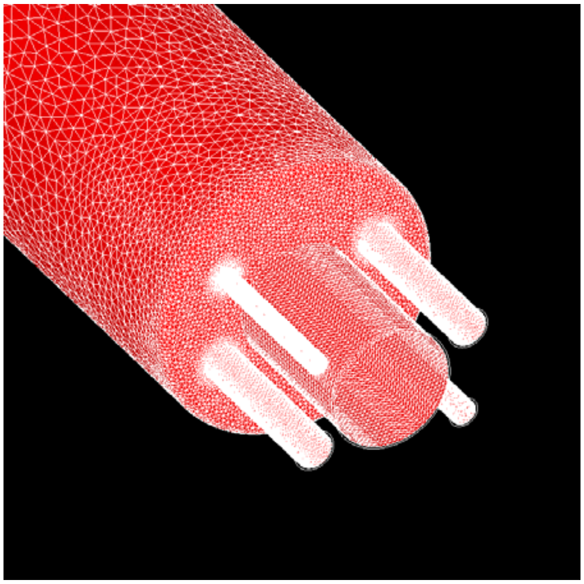

Figure 2. Drilling riser model showing surface mesh

rather than a complete description of the effect of heading. The two heading chosen (0 degrees and 60 degrees) are shown in Figure 3 assuming that the current direction is from left to right. The section length used for the simulations of the slick sections is 6.096m.

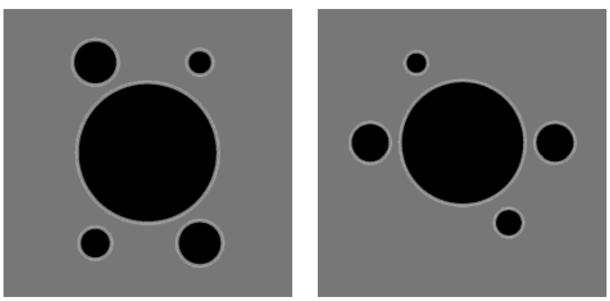

Figure 3. Heading 0 (left) and heading 60 (right) with current from left to right

The buoyancy sections were modeled to include a rounded shoulder on the end and included short sections of the drilling riser with auxiliary lines as shown in Figure 4. The buoyancy module is 21.36m long and the total section length including the protruding drilling riser sections is 22.86m. Note that all buoyancy sections are modeled with a heading of 0 degrees for the drilling riser.

NUMERICAL METHOD

All of the solutions shown here were produced using the AcuSolve^{TM} finite element CFD solver. AcuSolve is based on the Galerkin/Least-Squares formulation and supports a variety of element types. AcuSolve uses a fully coupled pressure/velocity iterative solver plus a generalized alpha method as a semi-discrete time stepping algorithm. AcuSolve is second order accurate in space and time. We used the Spalart-Allmaras turbulence model in all of the simulations. Wall functions are used to reduce the computational effort at the wall. The assumed wall roughness height is 1mm. for all elements in the riser. Figure 5 shows a typical fluid mesh used in the simulations. A slick section is shown but the same general meshing scheme is used for all simulations including combined sections. Note the wide wake area in the mesh intended to capture the wake when the transverse oscillations are large. As shown, the slick joint section uses 765,000 nodes while the somewhat longer buoyancy section mesh uses about 700,000 nodes. Meshes for combined slick and buoyancy sections typically used several million nodes.

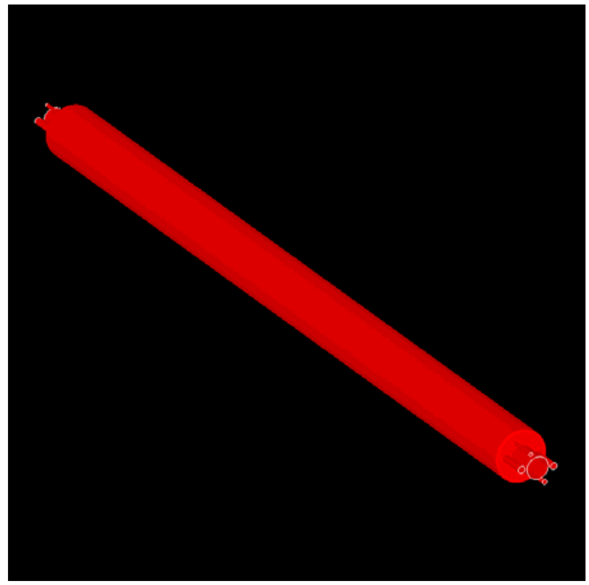

Figure 4. Buoyancy section

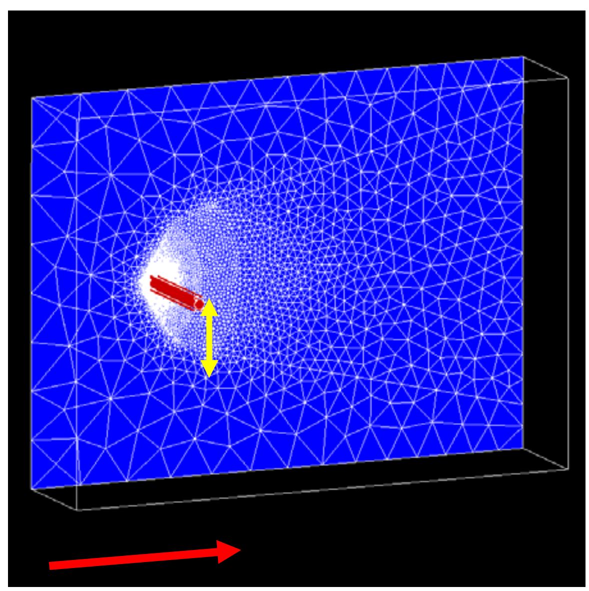

Figure 5. Overview of mesh for forced vibration study showing slick joint at 0 degrees heading. The red arrow indicates the current direction, the yellow arrow, the forced motion direction.

Copyright © 2008 by ASME

In the forced vibration simulations the mesh is moved using a user defined function which moves the nodes in the mesh at the beginning of each time step. The mesh motion simulates a sinusoidal cross flow motion of the riser. In the simulations reported here we used a period of vibration of 5 seconds which is the estimated vortex shedding period of a buoyancy section at a current speed of 1.27m/s.

As shown, the problems use a specified inlet velocity and non-reflective outlet boundary conditions. The side walls use a slip boundary condition and periodic boundary conditions are used at the top and bottom ends of the mesh. Note that the total blockage of the mesh in all cases is less than 5%.

Flow visualization was used to examine the vortex shedding patterns in the various runs. These varied a great deal with section type, heading and current speed so we don't attempt to describe this data here. As might be expected, the large cylindrical buoyancy sections show vortex shedding characteristics that are similar to simple cylinders, i.e. they show vortex shedding over a range of current speeds with strong associated forces on the sections. The slick sections on the other hand show a more complex vortex shedding behavior which varies with heading and current speed. Figures 6 and 7 show z-vorticity contours around slick sections in free, 2 degree-of-freedom (DOF) vibration at two headings but at the same current speed. In this case the vortex street for a heading of 0-degrees shows alternate single vortex structures forming immediately behind the riser (Figure 6). At a heading of zero degrees, the simulations predict a strong VIV response at this current speed. Figure 7 shows the similar vortex structure at a heading of 60 degrees. The vortex structures tend to remain attached to the riser for long periods of time. The predicted VIV response was low at this heading and current speed.

FORCED VIBRATION

A series of 72 numerical experiments were completed for slick sections and buoyancy sections over a range of current speeds and forced motion amplitudes. All of the simulations reported here use a motion period of 5 seconds. The lift in phase with velocity (Clv) was found for each run. In presenting this data we calculate lift coefficient based on the current speed and a frontal area based on the length and the assumed hydrodynamic diameter. In the case of the buoyancy sections this is 1.27m or the diameter of the buoyancy section. In the case of the slick sections, we use an average diameter of 0.8 *regardless of the heading*. This diameter is equal to the sum of the riser diameter plus twice the average choke and kill line diameter. Thus the actual frontal area is greater (0.864m) for a heading of 0 degrees and slightly less (0.737m) for a heading of 60 degrees. However, the use of a single effective diameter makes comparisons simpler here.

The results are summarized in Figures 8 to 10. In viewing the results it is useful to keep in mind that the buoyancy sections have about 60 percent more frontal area than the slick sections so forces on these sections are proportionately (~1.6 times) higher for the same lift coefficient. Also, in calculating the coefficients, the same frontal area is used for all slick sections regardless of heading.

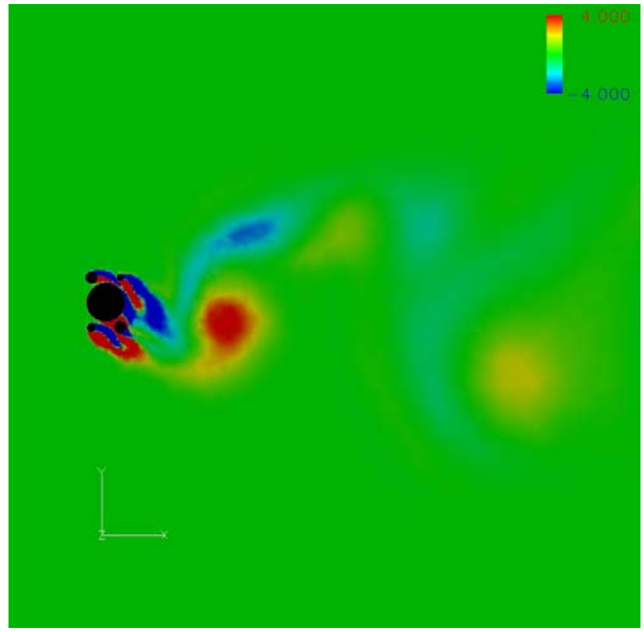

Figure 6. Z-vorticity contours: U = 1.0m/s- 0 degrees

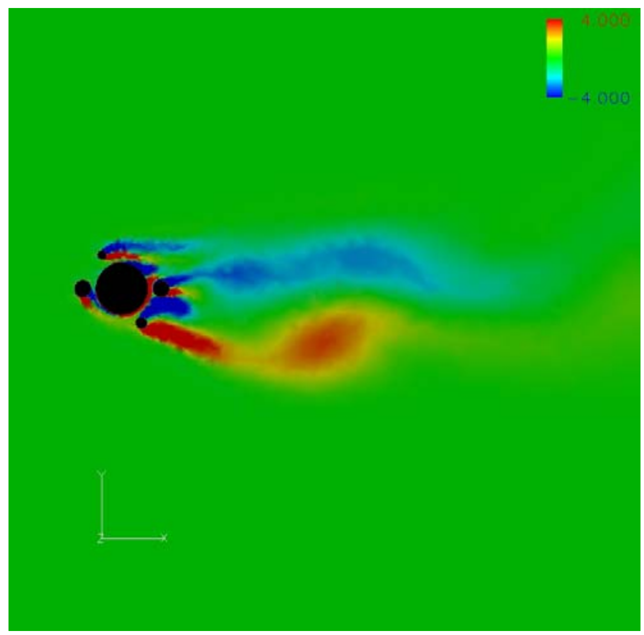

Figure 7. Z-vorticity contours: U=1.0m/s- 60 degrees

Figure 8 shows lift coefficients for the buoyancy section. We do not plot reduced velocity here because the diameter of the sections varies with section type and heading, but it is useful to keep in mind that the buoyancy sections with a diameter of 1.27m would have a reduced velocity of 5 at a current speed of 1.27m/s. The data show that these sections are power in sections with positive C_{lv} for most combinations of current speed and vibration amplitude tested here except at the largest vibration amplitudes.

Copyright © 2008 by ASME

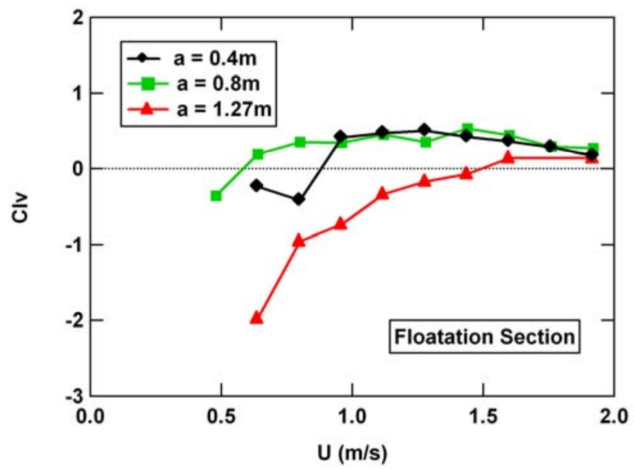

Figure 8. Buoyancy section lift in phase with velocity

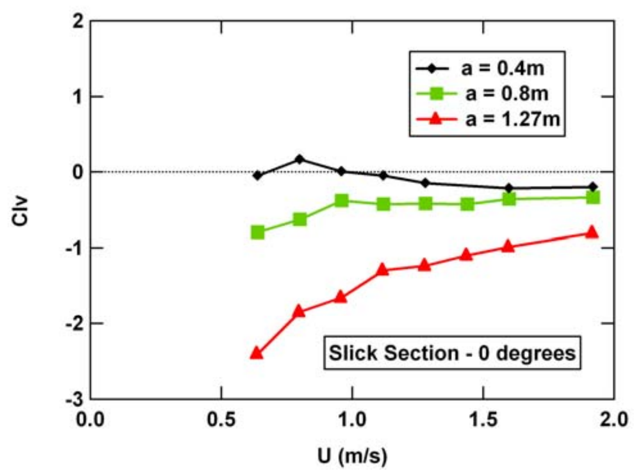

Figure 9. Slick section lift coefficient – heading 0 degrees

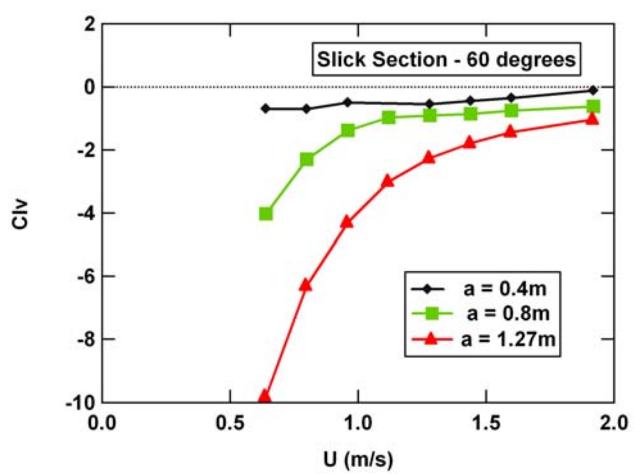

Figure 10. Slick section lift coefficient – heading 60 degrees

The slick sections (Figure 9 and 10) show a somewhat different behavior. In most cases, where the current speed is high and the amplitude of vibration is high these sections show negative values for C_{lv} indicating they will act as damping sections. The lift in phase with velocity has a large negative value in some cases suggesting that the slick sections might act as efficient energy dampers. However, this is tempered by the fact that the effective frontal area of these sections is 37% less than that of the buoyancy sections so the associated forces are smaller. In general, the forced motion of the slick sections must be large to see large negative values of C_{lv} so the damping effect will only be large if the vibration amplitude is already high.

FREE VIBRATION

The data for forced vibration show a variety of behaviors for buoyant and slick sections and also a significant variation in behavior over the two headings. In general, the lift in phase with velocity for the slick sections is negative over a range of amplitudes and current speeds. This suggests that the staggering of the buoyancy sections might reduce the overall riser response by interspacing sections with different properties and introducing more damping. Thus, while the buoyancy sections might be acting as "power-in" sections at a specific current speed, adjacent slick sections might act as dampers or "power-out" sections. In order to test this hypothesis, we performed a series of simulations where buoyancy sections and slick sections are joined together. The sections are mounted on springs allowing motion in the in-line and cross-flow directions. The spring constants are chosen so that the natural period of vibration in the cross flow direction (including the added mass effect of the surrounding fluid) is 5 seconds, the same as the period used in the forced vibration tests. The spring constants in the in-line direction were chosen so that natural period of vibration in the inline direction was 2.5 seconds.

The first simulations of free vibration were completed on the individual buoyancy sections (100% coverage) and on the slick sections at the two headings (0% coverage). We compare the root mean square (RMS) of the cross flow displacement to look for the effects of section type and heading in Figure 11. The data show that the RMS amplitude of the buoyancy section increases rapidly with current speed in the range of speeds studied. On the other hand, the slick sections show a strong dependence on heading. At 0-degrees heading, the slick section shows a strong VIV responses at low current speeds but this diminishes as current speed increases above 1m/s. At a heading of 60 degrees the VIV response is low at low current speeds but increases monotonically with increased current speed.

Copyright © 2008 by ASME

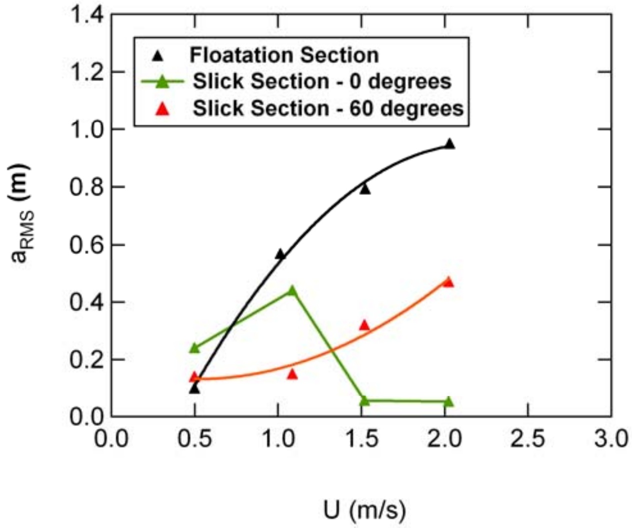

Figure 11. Free vibration of buoyancy and slick sections

Simulations were performed for riser systems consisting of alternate buoyancy and slick sections. The first trials were completed for a system with 77% buoyancy sections by length and 23% slick sections. These trials showed that the staggering had an effect, but not quite the one expected. In particular, the introduction of 23% slick sections decreased the in-line motions at either heading by about 50%. The cross flow motions increased slightly for a heading of 0 degrees and remained about the same for a heading of 60 degrees. The trajectories for the buoyancy section (100% coverage) and for the staggered sections are shown in Figure 12 at a single current speed to illustrate this point. Note that the inline mean position is shifted here for plotting purposes and does not reflect the actual in-line relative position.

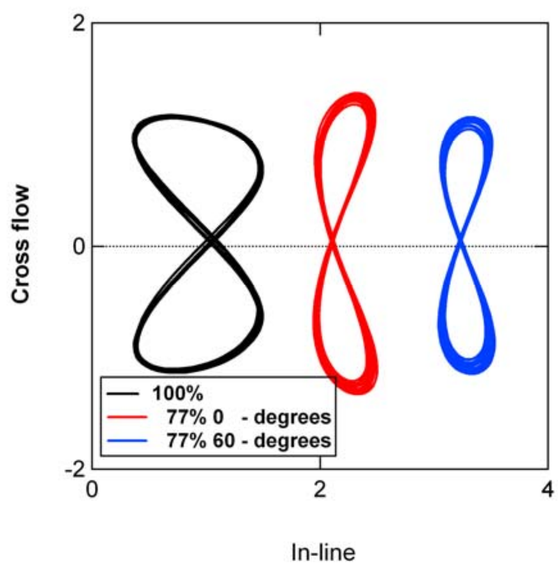

Figure 12. Trajectories with varying percent buoyancy and heading; U = 1.52 m/s

Further simulations were run at the two headings for 77% buoyancy coverage and 60% coverage. Figure 13 presents RMS cross flow displacements for these combinations of buoyancy and slick sections. These simulations were made by combining the sections as required to get the desired combined sections. Typically, the meshes employed several million nodes. As shown in the Figure 13, combined sections show cross flow RMS vibration amplitudes that depend on the amount of buoyancy and heading. None of the data suggest that short combined sections are free of VIV. However, the data do suggest that decreasing the buoyancy percentage from 77% to 60% decreases VIV. This can be seen by comparing the 77% coverage values (filled symbols) with the 60% coverage values (open symbols). The effect appears to be stronger at a heading of 60 degrees (red) than at a heading of 0-degrees (green). In-line motions for 60% coverage are also slightly reduced from those seen with 77% coverage.

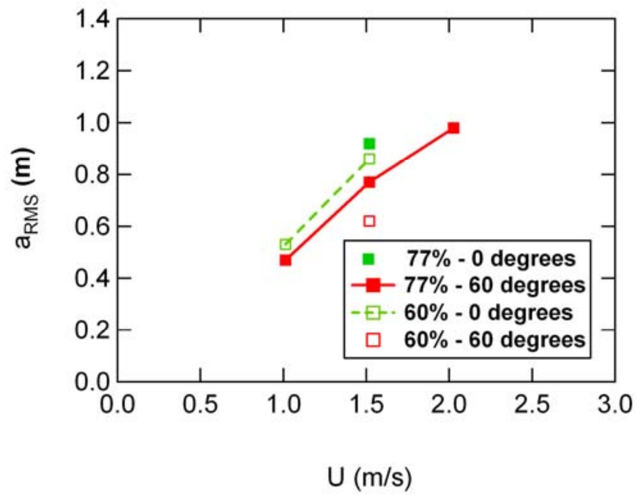

Figure 13. Cross flow vibration of combined sections

Although the results presented here do not indicate that staggering the buoyancy sections will eliminate VIV, they do show that this technique can alter the riser VIV characteristics. All of the simulations reported here were done in uniform currents and assuming relatively short rigid riser sections. It may be that the benefits of staggered buoyancy are more easily seen in sheared currents where careful planning can reduce the effect of power-in sections of the riser and increase the damping characteristics elsewhere. These effects could be the object of future studies of staggered buoyancy effects. It is also noteworthy that near the current speed where the buoyancy sections are expected to lock-in, i.e. where their cross flow vortex shedding period coincides with the natural period of the mechanical system, the addition of slick sections seems to significantly reduce in-line motions.

The current study does not seem to point to a simple approach to use buoyancy staggering to reduce drilling riser VIV. The data derived here is not sufficient to generate a general model of the forces on a drilling riser as a function of the flow conditions and riser motion and does not seem to lend itself to simple interpretation. It may be possible to model a relatively

Copyright © 2008 by ASME

long drilling riser under sheared flow using the methods outlined in Reference 5 and in fact the mesh strategy used here is designed to permit this. However, we have not undertaken this type of study yet. Such simulations combine a 3D fluid flow simulation with a linear riser structural model and are estimated to require CFD simulations using 5M nodes or more for relatively short sections of drilling riser. Finally, the simulations do show some benefit from staggering buoyancy sections and thus introducing slick sections to the riser. It may be possible to further change the hydrodynamic characteristics of the slick sections to enhance their beneficial effects.

CONCLUSIONS AND RECOMMENTATIONS

Simulations with short sections in forced vibration have shown that buoyancy sections behave much the same as bare cylindrical risers. Their large diameter means the exciting frequencies in most currents are low with periods on the order of several seconds. Slick sections show a range of behaviors depending on heading for the arrangement of the choke and kill lines used here. These sections show VIV in free vibration and may act as power-in or power-out sections depending on the current speed, heading and vibration amplitude.

We found that slick sections act as power-out sections over a range of conditions and thus tend to damp out vibrations. However, the amount of damping is not high enough to be considered a solution for riser VIV. Thus it appears that staggering the buoyancy modules along the drilling riser does not provide a significant uniform and easily identifiable benefit for the geometry and the uniform current cases studied here. However, design changes in the slick section might be used to increase their damping effectiveness. For example, changes in the arrangement of the choke and kill lines might be used to effectively reduce the vortex shedding behavior of the slick sections. Also, added hydraulic components might also be used to increase the damping of these sections. Furthermore, the buoyancy sections might be made shorter to increase end effects and reduce their susceptibility to VIV.

Finally, the CFD simulations discussed here provide an inexpensive way to generate hydrodynamic characteristics of riser components. These characteristics can be used to estimate riser VIV using analytic models. However, the results also show that the riser component behavior is complex, depending on heading and the motion (e.g. 1DOF vs. 2DOF) of the riser.

Although we did not discuss it here, the meshes used for this study are designed to be combined to model a long flexible drilling riser with staggered buoyancy combining a three dimensional CFD simulation with a linear structural model as discussed in [5]. We did not have time to complete this type of simulation here but it is certainly within current capabilities. Such a problem might model the upper part of a drilling riser in a sheared surface current rather than the entire riser in order to keep the problem size manageable.

REFERENCES

1. Brooks, I. H., (1987), “A Pragmatic Approach to Vortex-Induced Vibrations of a Drilling Riser,” OTC 5522, Offshore Technology Conference, Houston.

2. Vandiver, J. K and Peoples, W., (2003), “The Effect of Staggered Buoyancy Modules on flow-Induced Vibration of Marine Risers,” OTC 15284

3. Vandiver, J. K, Swithenbank, S. B., Jaiswal, V. and Jhingran, V, (2006), “Fatigue Damage from High Mode Number Vortex-Induced Vibration,” OMAE2006-92409 ,Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering

4. Vandiver , J. K, J. K, Swithenbank, S. B., Jaiswal and Marcollo, H.(2006) “The Effectiveness of Helical Strakes in the Suppression of High-Mode-Number VIV,” OTC 18276, Offshore Technology Conference, Houston.

5. Constantinides, Y., Oakely, O. H. and Holmes, S., (2007), “CFD High L/D Riser Modeling Study,” OMAE2007-29151, Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering.

Copyright © 2008 by ASME